Fast SE/TSE/RARE, refocusing with low flip angle pulses

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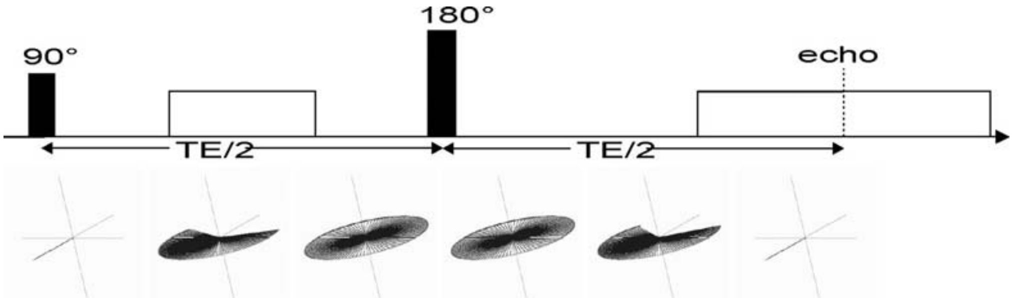
1 Introduction

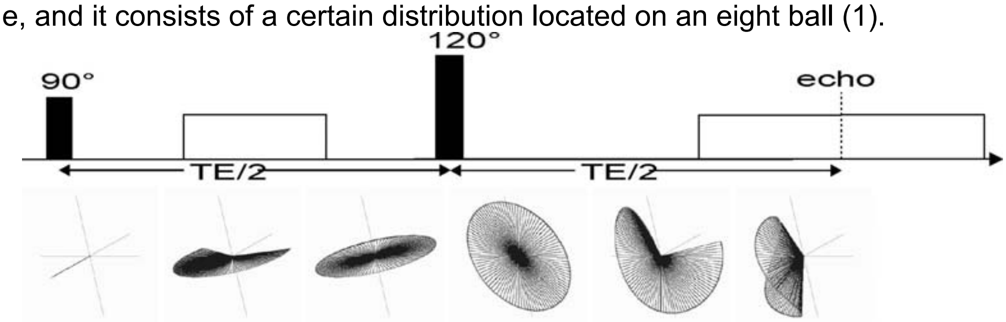
The spin echo is a fundamental principle (1) that can be used for magnetic resonance imaging. Spin echo techniques are characterized by at least two rf-pulses. The first rf-pulse acts as an excitation pulse that converts longitudinal magnetization into transverse magnetization, and a second rf-pulse after TE/2 is used as a refocusing pulse that (partially) inverts the accumulated phase between excitation and refocusing, and a spin echo is formed at TE (TE/2 after refocusing pulse). The basic principles of spin echo formation are relatively simple and clear. However, description and evolution of magnetization becomes much more exciting and interesting with the use of several refocusing pulses as used in fast spin echo techniques such as TSE, RARE, or FSE. Especially the use and optimization of low-flip angles refocusing pulses to reduce SAR in high-field applications has driven the development of new techniques such as Hyperechoes and TRAPS.

2 One refocusing pulse

For the ideal 90° - TE/2 – 180° - TE/2 combination, the 90° excitation pulse converts the longitudinal magnetization fully into transverse magnetization. After TE/2 each dephased magnetization vector is rotated by 180°, and the spin echo at TE consists of a single magnetization vector along x- or y-direction. The length of this vector is reduced compared to the initial length after excitation by non-static effects such as T2 and diffusion, which cannot be refocused by the second pulse. Static effects (i.e. chemical shifts or field inhomogeneities) that are constant during 0…TE are fully refocused at TE. If the flip angle of the refocusing



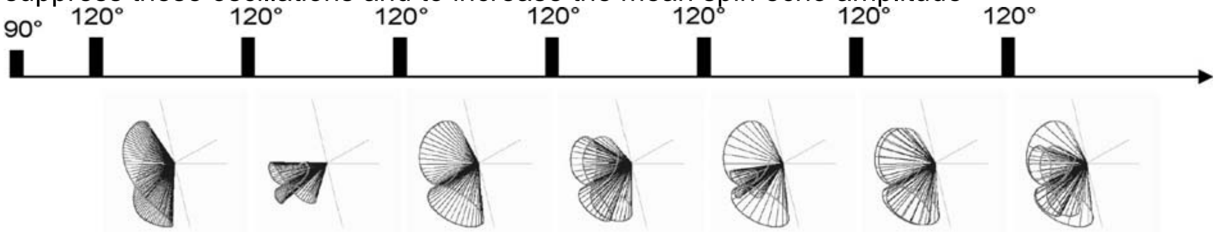
pulse is reduced, for example, to 120° the magnetization is split into a longitudinal and a transverse part. As a result, the echo amplitude is reduced compared to the previous example, and it consists of a certain distribution located on an eight ball (1).



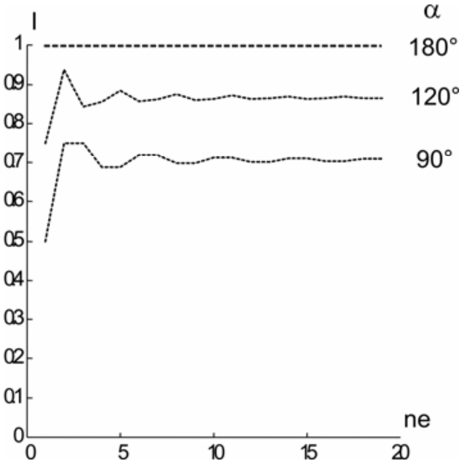
3 More refocusing pulses

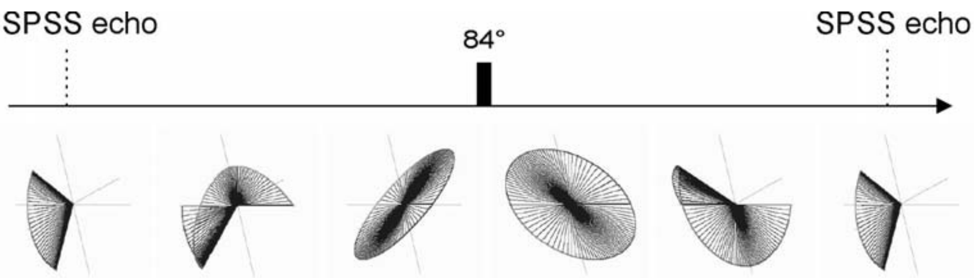
In most cases magnetization is not fully relaxed after one refocusing period, and further refocusing pulses can be applied to generate a train of spin echoes. This principle (CPMG, RARE, TSE, FSE) is often applied for T2-weighted sequences to reduce imaging time. In the case of 180° refocusing pulses no longitudinal magnetization (stimulated echoes) is generated, and the decay of spin echo amplitudes is solely given by T2 (and diffusion effects) (2,3). In some cases the flip angle of refocusing pulses has to be reduced to reduce

RF-power deposition. Since rf-pulses less than 180° act simultaneously as refocusing and excitation pulse magnetization is successively split into more and more transverse and longitudinal components. As a result, echo amplitudes show oscillations within the transient phase of the first refocusing pulses and have a reduced amplitude compared to 180° refocusing pulses. Furthermore, the decay of spin echo amplitudes now is not only given by T2, but depends on both T1 and T2. Signal oscillations produced by low-flip angle refocusing pulses may produce imaging artifacts, and several strategies have been developed to suppress these oscillations and to increase the mean spin echo amplitude



The behaviour of TSE, FSE, .. sequences with reduced refocusing flip angle can be described more easily if relaxation is ignored. Simulation of spin echo amplitudes as a function of the echo number for different refocusing flip angles demonstrate that a so-called pseudo steady state (PSS) will be established after an initial phase of echo amplitude oscillations. The PSS is characterized by a constant spin echo amplitude that is given by $M_0\sin(\alpha/2)$, if α is the refocusing flip angle (3,4). The PSS is characterized by the fact, that only the total magnetization defined by the integral over all isochromats as a function of the offresonance frequency will reach a steady state value, whereas each single isochromat will perform a quasi-periodic trajectory. Thus, distribution of magnetization gets more and more complicated while the spin echo amplitude is constant. It has been shown, that the pseudo-steady state reached by consecutive constant refocusing pulses is not unique for each α, but depends on the initial preparation of the spin system. This has been exploited by LeRoux (5) and Alsop(4), who have described methods to arrive at even higher pseudo steady state amplitudes by using variable refocusing flip angles converging to a over the first refocusing periods. More recently it was demonstrated that even setting only the first refocusing flip angle to $90+\alpha/2$ will already produce amplitudes, which are very close to the maximum obtainable signal (6). A different type of steady state where each isochromat is an identical copy from echo to echo (as for the steady state in gradient echoes) can be produced with train of refocusing pulses with decreasing flip angles converging to the final flip angle α. The resulting, so-called static PSS (SPSS) gives the highest spin echo amplitude of all possible refocusing schemes. At the time of spin echo refocusing each isochromat of the SPSS distribution is located on a segment of a circle in x-z-plane (or y-z-plane).

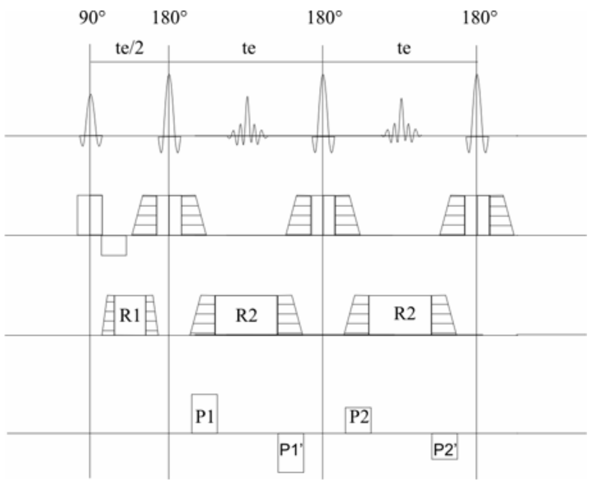


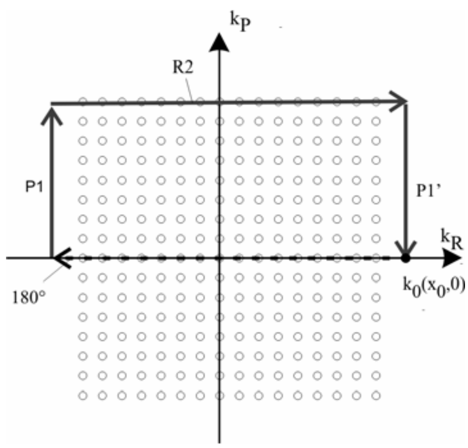


A new approach called Hyperecho-TSE (7) allows to perform multiecho-imaging without any signal loss at considerably reduced RF-power by making use of symmetry relations along multipulse sequences. In a practical implementation this allows to acquire images at identical S/N with 20-25% of the RF-power of a fully refocused sequence. In the regime of echo train length 20-256 a new approach called TRAPS (transition between pseudo steady states) can be applied, which allows to modulate the refocusing flip angles along the echo train to produce high intensity (at the cost of high flip angles) only for the 'important' data at the center of k-space and low intensity elsewhere. Depending on the actual implementation the savings in SAR can be as much as a factor of 10 for single shot sequences (HASTE, SS-TSE) and 40-70% for segmented scans without signal loss (8).

4 The fast spin echo imaging sequence

The essential issue in setting up a RARE(TSE, FSE…)-sequence shown right is the requirement to bring the spin system into exactly the same state of dephasing prior to each refocusing pulses. With respect to field inhomogeneities this is achieved by observing the correct timing of the CPMG-sequence (9). With respect to the switched gradients used for spatial encoding, this has to be taken care of by proper design of the sequences. For the read- and phase-encoding direction the necessary refocusing conditions can be directly derived from the k-space representation of the sequence. Specifically, the integral over the readout gradient R2 between successive refocusing pulses must be twice the integral over R1. The 'meeting point' k0 of all magnetization is best placed on the kp=0 axis, which leads to symmetrical phase encoding vs. rewinder gradients: P1' = -P1 etc. This phase encoding rewinder is the most essential feature to ensure artifact-free images.





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